Vehicle Coastdown Resistance Analysis Under Windy and Grade Variable Conditions

Final Report

on

Transport Canada Contract
No. T 8080-7-2232/01-SS

by

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October, 1988

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ABSTRACT

A testing and analysis method has been developed for the evaluation of the aerodynamic and rolling resistance coefficients of a vehicle, under windy weather conditions and on a road with considerable variation in grade. Over 100 coastdown runs have been collected and analyzed for the Transport Canada Nexus research prototype. Aerodynamic and rolling resistance functions have been found for the test vehicle for conditions from zero to over 30 degrees yaw, noting a phenomenon in which aerodynamic drag decreases with yaw angle for Nexus. In addition, the effects of vehicle centripetal force, lift force, velocity effects of rolling circumference and the velocity dependence of rolling resistance are discussed. The data analysis method developed, uses a computer based simulation/optimization technique, which is described in this paper. This new resistance analysis technique will enable vehicles to be studied under typical non-ideal road and weather conditions.

RÉSUMÉ

Une méthode d'essai et d'analyse a été développée pour évaluer les coefficients de résistance aérodynamique et de roulement d'un véhicule, sous des conditions où la direction et la vitesse du vent ainsi que la pente de la route varient considérablement. Plus de 100 essais de décélération en roue libre furent accumulés sur le prototype de recherche Nexus de Transports Canada et les résultats furent analysés. Des relations mathématiques furent établies pour les résistances aérodynamique et de roulement pour de conditions où l'angle d'incidence du vent variait entre 0 et 30 degrés avec l'axe du véhicule; on a noté que la résistance aérodynamique décroissait avec un accroissement de l'angle d'incidence du vent. De plus, les effets de la force centripète, de la force de poussée, et de la vitesse sur la circonférence de roulement et la résistance au roulement sont discutés. La méthode d'analyse utilse une méthode de simulation et d'optimisation sur ordinateur; cette méthode est décrite dans cette communication. Cette nouvelle technique pour analyser les forces de résistances permettra l'étude de véhicules sous des conditions plus typiques (et non-idéales) de route et de climat.

Résumé traduit par Systèmes des Véhicules, Transports Canada.

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DISCLAIMER

The contents of this report reflect the views of the authors and not necessarily the official views of Canada's Panel on Energy Research and Development nor those of the Road Safety and Motor Vehicle Regulation Directorate of Transport Canada.

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INTRODUCTION

Coastdown testing has long been an effective means for determining vehicle resistive forces. These resistive forces arise mainly from aerodynamic drag and rolling resistance but can be added to by brake drag, wheel misalignment and driveline drag. Coastdown tests provide a check on wind-tunnel drag measurements, and laboratory rolling resistance measurements. Results obtained from coastdown tests can be more meaningful than laboratory tests because even if the effects of wind fluctuations, toe-in, etc. are not being modeled, they are significant in absorbing transportation energy.

Coastdown tests under windy conditions have been conducted by Buckley et. al. [1] on tractor-trailer trucks, with success in evaluating the yaw dependency of aerodynamic drag. They were unable however, to experimentally determine vehicle rolling resistance so an analytical model was used to extract this force from the coastdown data. The ability to perform coastdown tests in windy conditions permits greater flexibility in the test program, allowing testing to occur on windy as well as windless days.

Drag versus yaw characteristics of the vehicle can be obtained if proper steps are taken to record the vehicle aerodynamic speed and direction. A vehicle on the road seldom experiences a condition of zero yaw angle. For this reason, a more important characteristic of the vehicle is its wind mean average drag coefficient (WMAD) [2] and not simply its usually quoted drag at zero yaw.

Another problem with coastdown testing has been the need for a 'level' road on which to perform tests. The SAE Recommended Practice J1263 [3] (Road Load Measurement and Dynamometer Simulation Using Coastdown Techniques) suggests that coastdown runs be performed on a road with a constant grade of up to 0.5%. It recommends however, that runs be paired in opposite directions so that grade influences may cancel out. The authors believe however, that practically any road can be used to perform coastdown tests if the instantaneous grade influence is taken into account. This means that the road must be surveyed and the position of the vehicle on the road during the coastdown be known. If this is done, acceptable results can be obtained in finding vehicle resistance factors. This will alleviate the need for researchers to spend large amounts of time and money finding an appropriate road upon which to have coastdown testing done.

This study has used the coastdown method and a unique data analysis technique to determine vehicle resistance factors under windy and grade variable conditions. Aerodynamic drag factor and rolling resistance values have been obtained for the University of Saskatchewan designed, Transport Canada Nexus commuter prototype [4]. The Nexus commuter car (Figure 1), was chosen to perform tests because it represents a 'new generation' of fuel-efficient safety oriented single passenger road cars.

Figure 1 Nexus commuter prototype

The sleek aerodynamic design, three wheel configuration and light weight of Nexus make it a 'worst case' for which to measure resistance. Johnston [5] has shown that its light weight and low aerodynamic drag, make these values more difficult to measure accurately and repeatedly. Therefore, if repeatable results could be obtained with the Nexus vehicle, genuinely good results should be expected for almost any commercial road vehicle. Another reason for selecting the Nexus vehicle is that Johnston had already performed coastdown tests with it on a level road, so there would be comparable data available.

This paper will present a simple method for performing and analyzing coastdown tests conducted on a road with varying grade, under windy conditions. These results will show this to be a practical and viable solution to the problems associated with coastdown testing. It will enable tests to be performed on practically any smooth road, under any wind conditions. The method will give more complete information about the vehicle resistance factors, including what happens at aerodynamic yaw, a condition almost always encountered on the road.

TEST ROAD

A great deal of consideration went into the selection of an appropriate road upon which to perform the coastdown tests. It was important that the road be smooth, in good condition, close to our university, and lightly travelled by other traffic. Furthermore, a road whose grade characteristics did not comply with SAE Recommend Practice for Coastdown testing (SAE J1263), was desired. The reason for this, was that the authors wished to show that good results could be obtained

from coastdown tests on a typical road with a considerable grade and elevation change. This was to be accomplished with a unique computational analysis technique, taking road grade into account at each place a distance-time point was recorded.

Figure 2, is an elevation profile of the road selected for coastdown testing. As can be seen in the figure, the grade is not constant along the track. On the steepest part of the track the measured grade is about 0.7%. This section of road was surveyed, before testing began, to an elevation precision of $\pm$1.0 mm, every five meters on both the East and West bound lanes.

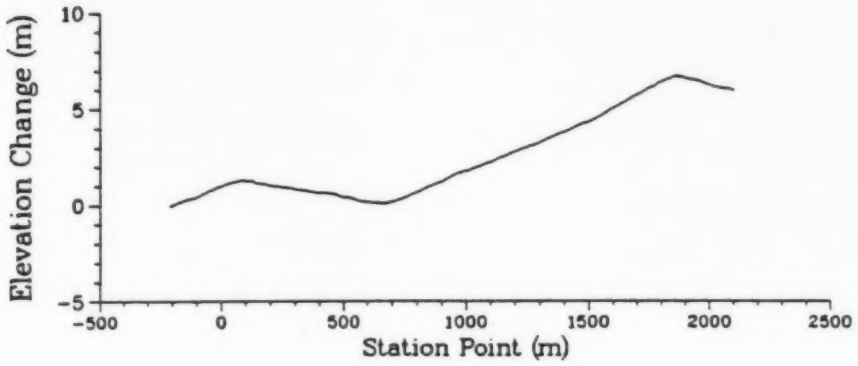

Figure 2 Elevation Profile of Coastdown Track

DATA ACQUISITION AND INSTRUMENTATION

Because of the small size and light weight of the Nexus test vehicle, the data acquisition system and instrumentation had to be compact and precise. The magnitudes of resistances being measured in this case would be much less than that of a standard passenger vehicle. The data acquisition system chosen for use during coastdown tests was a Campbell Scientific 21X micrologger storing data to cassette tape.

The Campbell micrologger provided the small size, light weight and flexibility needed to monitor and record several channels of analog and digital data. The system allowed the user to download the acquired data from cassette tape to an IBM PC compatible computer for analysis. In this case, the data was further uploaded to a Digital Equipment, Vax 8600 mainframe computer for processing.

The complexity of the instrumentation was kept as low as possible for the simple reason that complexity adds weight and problems. As mentioned earlier, the parameters measured on the test vehicle were:

- position on the road,
- distance-time data,
- aerodynamic velocity,
- and yaw angle.

Before discussing the instrumentation used, it would be appropriate to describe the method used to trigger the acquisition system in order that vehicle position be known. The triggering device used a photo-optic pickup, aimed at the road beneath the car. The pickup was about 15 centimeters from the road surface, placed inside a cooling duct open at the bottom, so as not to interfere aerodynamically. The device toggled a voltage line high to the micrologger when a white stripe painted across the road was sensed by the photo-optic sensor. When the voltage from the trigger was sensed high by the micrologger, data acquisition was begun. Data acquisition was stopped by having the driver manually reset the trigger.

With a stripe 20 centimeters wide on the road, the trigger proved to work reliably even at speeds in excess of the normal starting speed of 100 km/h.

Distance, was measured digitally using a magnetic pickup, triggered by a slotted disk in place of the rear brake disk of the vehicle. The disk was slotted with 117 targets giving a road distance resolution of about 1.6 centimeters. The pulse signal from the magnetic pickup was sampled by the micrologger every 0.1 seconds during a coastdown run, the sum of five of such samples was recorded to cassette every 0.5 seconds.

Dynamic tests were performed over a 1700 meter distance to determine the tire circumference and calibrate the pulse counter. Ten coastdowns were done from 100 km/h to about 30 km/h, with all tires pressurized at 414 kPa, recording the number of pulses obtained from the rear target disk. The rolling tire circumference was found to be 1.841 meters with a sample standard deviation of 0.001 meters. In addition to these dynamic tests, four static circumference tests were performed by rolling the car, with driver, a total of 16 wheel rotations, about 30 meters. Under these conditions, the tire circumference, at 414 kPa was found to be 1.838 meters with a sample standard deviation of 0.001 meters.

Although the difference between static and dynamic tests seems to indicate that tire circumference is slightly velocity dependent, this difference of 3 mm would cause an error of less than 3 meters over the entire distance of a coastdown run. Further analysis, described later in this paper, has shown this error to be insignificant.

In order to perform coastdown tests in a windy environment a method of measuring vehicle aerodynamic speed and direction is essential. For these windy tests, aerodynamic speed was measured using a Kiel type [6], yaw insensitive pitot-static tube (YIPST) and a pressure transducer. A cross sectional drawing of the tube can be seen in Figure 3.

The tube was calibrated in the University of Saskatchewan wind tunnel and its yaw insensitivity was found to extend to beyond 50 degrees of yaw (Figure 4), the highest yaw angle thought to be encountered during testing. This test also showed the tube to indicate 1.5% higher velocity, on average, than a regular pitot-static tube, aligned with the flow. This difference was taken into account during data analysis.

The aerodynamic yaw angle of the test vehicle was measured using a vane that aligned itself with the wind, attached to a potentiometer. The voltage across the potentiometer was measured every 0.5 seconds during a coastdown run and recorded to cassette tape.

The aerodynamic velocity measuring equipment, (YIPST and vane) was mounted on a boom extending approximately one meter in front of and about mid height of the test vehicle (Figure 5).

In order to test for upstream interference of the velocity field measured by the YIPST due to the vehicle, a sensitivity test was

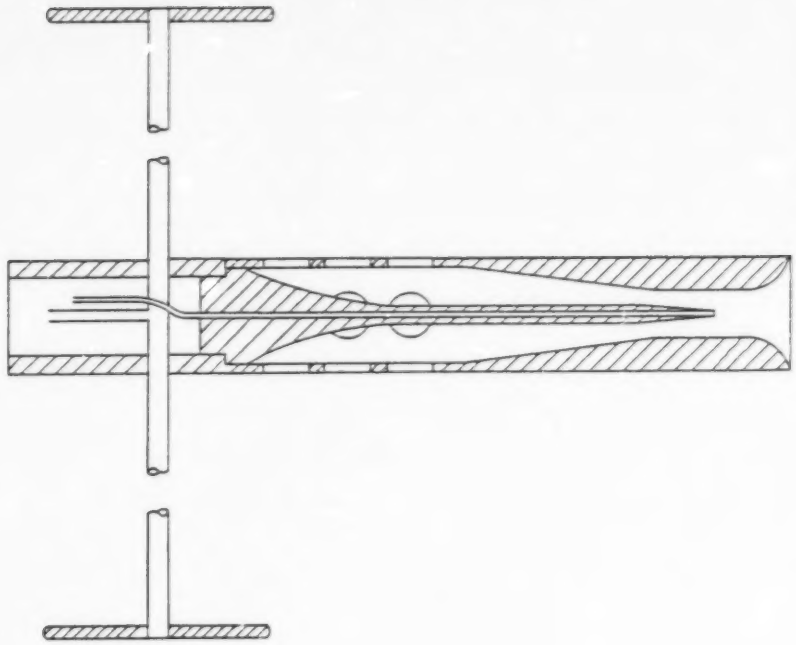

Figure 3 Yaw Insensitive Pitot-Static Tube

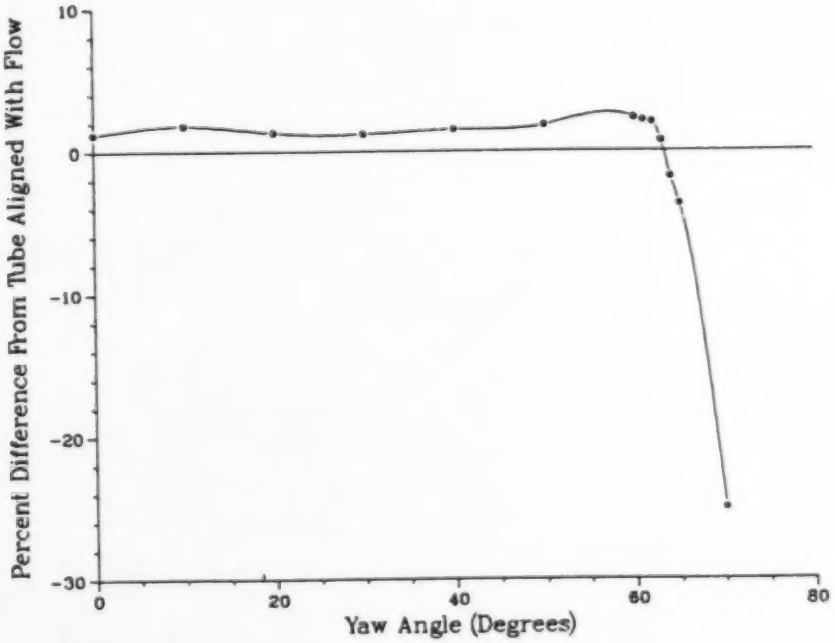

Figure 4 Calibration of Yaw Insensitive Pitot-static Tube

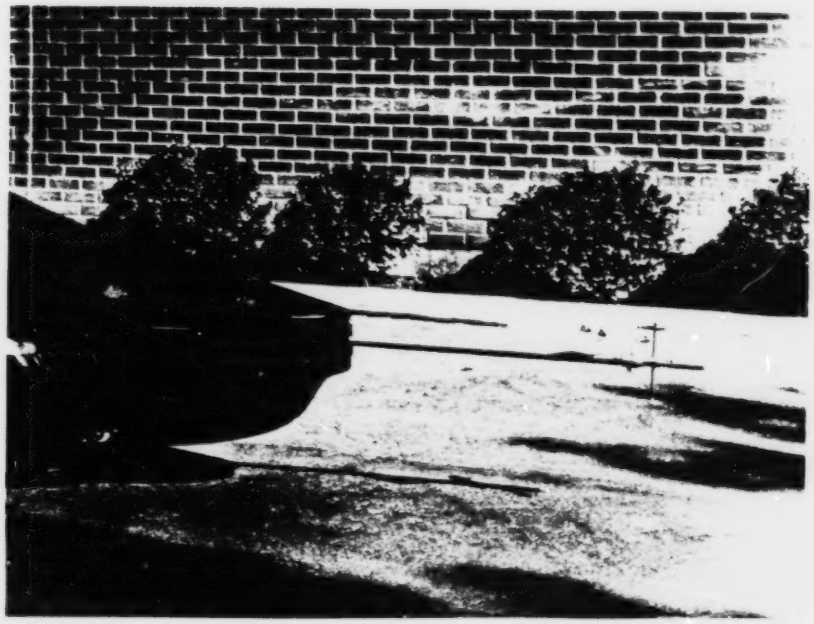

Figure 5 Boom and Velocity Measuring Instruments Mounted on Nexus Test Vehicle

conducted in the University of Saskatchewan wind tunnel. The test was performed by mounting a cylindrical, hot film anemometer probe 250 mm in front of a 1/4 scale model of the test vehicle. The hot film probe was aligned vertically to measure velocity only in the horizontal plane. The test was performed at several yaw angles and a comparison of the velocity measured by the hot film probe, and free stream can be seen in Figure 6.

Because this test indicates a small interference effect up to 20 degrees yaw, the indicated velocity was corrected during analysis. The correction assumed a linear relationship between indicated and true aerodynamic velocity up to 20 degrees yaw.

COASTDOWN PROCEDURES

The first consideration for the coastdown test of a vehicle is its ability to free-wheel. The idea of a coastdown test is to keep driveline drag to a minimum. For this reason, a free wheel was attached to the chain driven Nexus car between the drive sprocket and rear hub. This allowed the measurement of resistance due only to the tire-pavement interaction, the bearings, the free wheel itself and aerodynamics. To minimize the effects of outside sources of resistance, in particular the brakes, the rear brake was removed from the vehicle entirely and prior to each coastdown run, the front disc brake pads were backed off to prevent them from rubbing. Toe-in was also closely monitored and held constant at 0.36 degrees throughout the testing period.

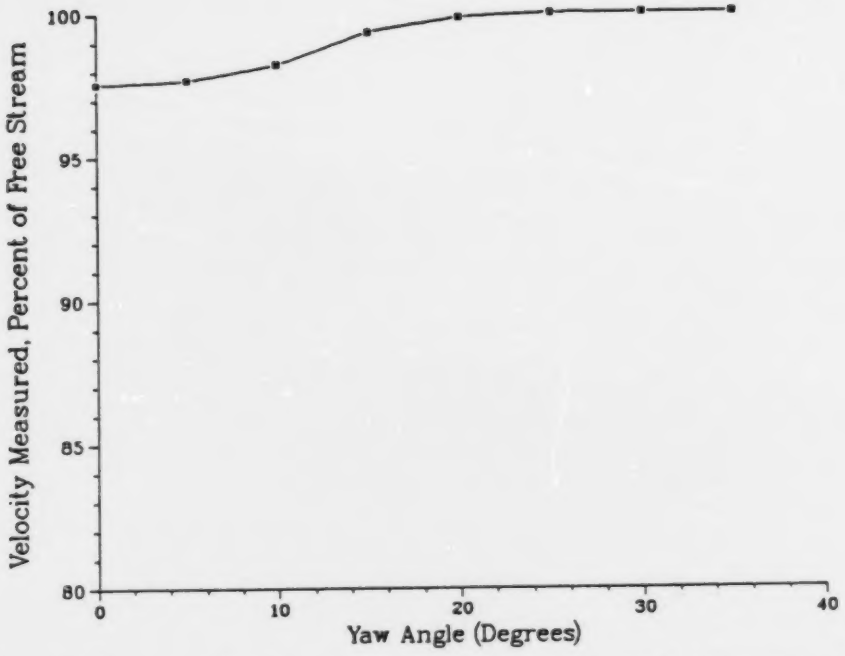

Figure 6 Upstream Interference Effects of Test Vehicle on Free Stream Velocity

In an attempt to be as thorough as possible, a strict set of rules were designed and followed for each day of coastdown testing. This set of rules was based upon the SAE Recommended Practice J1263.

A day of coastdown testing consisted of towing the vehicle approximately twelve kilometers to the test site. The car was towed to prevent undue stress on the delicate free wheel. The trip to the test site was long enough to bring the tires and bearings to operating temperature. Coastdowns were then begun by filling out the appropriate information on a test data sheet as seen in Figure 7. The front brakes would then be manually backed off and the driver would be allowed to begin a coastdown run.

A coastdown pair consisted of first driving the car to a speed of about 105 km/h. Just before the white stripe marking the starting point of the west run was met, the data acquisition trigger was armed, and engine power was removed from the car allowing it to coast. When the white triggering stripe was passed, data acquisition was automatically started and distance, relative air speed and direction were recorded every 0.5 seconds. When the vehicle had slowed to 30 km/h, the driver stopped the data acquisition system, ending the run. When it was safe to do so, the vehicle was turned around and a coastdown run in the opposite direction was begun. When the vehicle returned to its original starting location, the appropriate measurements were repeated and another coastdown pair was allowed to commence.

During the coastdown testing period, about half of the runs were made in so called 'calm' conditions. These were conditions such that the wind velocity did not exceed eight km/h.

During calm condition tests, the instrumentation measuring aerodynamic speed and yaw angle was not attached to the vehicle. A total of about 68 pairs of "calm tests" and 80 pairs of "windy tests", with aerodynamic velocity instruments attached, were performed.

COASTDOWN DATA SHEET

Vehicle Research Group

DATE: 1988

RUN NUMBER:

TIME:

TO BE NOTED EACH DAY:

Weights:

Front Left _____(kg)

Front Right _____(kg)

Rear _____(kg)

Total _____(kg)

Tire Pressures:

_____(psi)

_____(psi)

_____(psi)

Avear _____(psi)

Attitude - Front clearance _____(mm)

Rear clearance _____(mm)

TO BE NOTED EACH RUN:

Tire Temperatures:

Front Left _____(C)

Front Right _____(C)

Rear _____(C)

Average _____(C)

Road Temp _____(C)

Air Temp _____(C)

Barometric Pressure _____(kPa)

Humidity _____(%)

Sunny? ____ Cloudy? ____ Both? ____

Wind speed _____(km/h) From _____

COMMENTS:

Figure 7 Coastdown Data Sheet

VEHICLE RESISTANCE FACTORS

Several individual factors may contribute to the total resistance to motion of a vehicle. The basic resistance to motion equation for a vehicle is given by:

$$- M_e\, a = F_R + F_A + F_D + F_G \qquad (1)$$

Where M_e = equivalent mass of the vehicle, Kg
a = acceleration of the vehicle, m/s^2
F_R = rolling resistance force, N
F_A = aerodynamic drag force, N
F_D = drive line resistive force, N
and F_G = grade force, N.

To determine the effective mass, m_e, of the rotating components of the vehicle, the inertia, J, was measured as described in Reference 7. The equation

$$m_e = \frac{J}{r^2} \qquad (2)$$

where r = radius of tires

was then applied. The equivalent mass of the vehicle is then the sum of the mass of the vehicle with driver and the effective mass, m_e, of each

of the three wheel assemblies. The aerodynamic force on the vehicle, F_A, is the product of a drag factor, F_2 ($N/(m/s)^2$) and the aerodynamic velocity of the vehicle, V_a, squared (m/s),

$$F_A = F_2 V_a^2.$$

In the analysis, F_2 is corrected to standard atmospheric temperature and pressure.

The rolling resistance of a vehicle can be expressed as a function of the weight seen by the tires and the velocity, V, of the vehicle, (at constant tire pressure, temperature, load and slip angle) [8].

$$F_R = (F_0 + F_1 V), \tag{3}$$

where $F_0 = Cr W_e$, N
$F_1 = Cr_v W_e$, N/m/s
and V = vehicle speed, m/s.

In the above nomenclature, Cr and Cr_v are the coefficient of rolling resistance and the velocity dependent coefficient of rolling resistance respectively. The effective weight of the vehicle, W_e, is the normal force seen by the tire, on a road with a grade. This is,

$$W_e = W \cos \theta - F_L + F_C \tag{4}$$

where W = weight of the vehicle, N
θ = grade angle, degrees
F_L = lift force, N
and F_C = centripetal force, N, (positive down).

Since the test section grade changes with distance (i.e. has hills and valleys), there was concern that the centripetal force may have a significant effect on rolling resistance. For this reason, the centrifugal effect was looked at closely during analysis and is discussed later. Initially F_C will be said to be zero and F_1, the velocity dependent coefficient of rolling resistance, was allowed to remain part of F_0 and F_2.

A wind tunnel study was performed on a one quarter scale model of the Nexus test vehicle to estimate its lift factor. The test, performed on a stationary ground plane with no boundary layer control devices, indicated a lift factor of -0.0105 $N/(km/h)^2$. This study was carried out in order to estimate the effect of neglecting lift in the analysis of the coastdown data. The effects of lift are presented later in the paper.

A series of twelve coastdowns of the driveline components was conducted in order to determine the driveline drag, F_D, of the test vehicle. The test was conducted by suspending the rear of the car and accelerating the rear wheel to a speed of 100 km/h and allowing it to coastdown with freewheel and chain attached, while recording distance-time data. The distance-time data was then changed to velocity-time data by differentiation. This data was then analyzed by the CoastSAE program [3] to determine an F_0 constant coefficient and an F_2, velocity squared dependent coefficient. The results of this test are

$$F_D = 0.5 + .0002 * V^2 \text{ [Newtons, V in km/h]}.$$

Since the contribution of driveline drag to the total resistance force expected is so small, it was allowed to remain part of the rolling and aerodynamic resistance factors.

The grade force on the vehicle, F_G, would be changing with its location on the coastdown road. For this reason, the coastdown track must be surveyed, and the vehicle position on the road must be known for each distance-time data point recorded. From this information, the grade force can be evaluated by,

$$F_G = W \sin \theta. \tag{5}$$

Referring to what has been discussed, equation (1) can be simplified to,

$$- M_e\, a = F_R + F_A + F_G,$$

or
$$- M_e\, a = F_0 + F_2 V a^2 + F_G \tag{6}$$

Equation (6) was the starting ground for the coastdown data analysis. In equation (6), the only unknowns are F_0 and F_2.

DATA ANALYSIS

The method used for all data analysis was a simulation/optimization approach. This approach was also used successfully by Dayman [9] to assess tire rolling resistance from coastdown tests. This method was selected because it allowed calculation of several variables at once. Not only can coefficients for rolling resistance and aerodynamic drag be deduced, but it may also be used to solve for lift coefficient or the velocity dependent term of rolling resistance.

The new computer analysis programs developed [9] are called "COAST" for calm data and "COAST_WIND" for windy data. Both codes employ recursive simulation in which a computer generated coastdown distance-time curve is compared with the actual on-the-road coastdown curve. The analysis program is written in Vax FORTRAN and was run on a Digital Equipment, Vax 8600 computer.

The computer generated distance-time curve is arrived at using the vehicle resistance to motion equation,

$$- a = (F_0 + F_2\, V a^2 + F_G)/M_e \tag{7}$$

where M_e = vehicle equivalent mass, Kg
a = vehicle acceleration, $(m/s)^2$
F_0 = rolling resistance, N
F_2 = aerodynamic resistance factor, $N/(m/s)^2$
and F_G = grade force, N.

Acceleration is solved for in equation 7 and substituted into the equation,

$$V_{new} = V_{old} + a\, ti \tag{8}$$

where ti is the time increment for the computer program. However, before equation 8 is executed, a new distance is calculated by the

equation,

$$D_{new} = D_{old} + V\ ti. \qquad (9)$$

A new distance, D_{new}, is calculated each computer time step, ti, of 0.1 seconds during a simulated coastdown and after each 0.5 seconds it is compared to the coastdown data obtained for the on-the-road run. If the error between the simulated and on-the-road curves is too large, the simulation is repeated using new coefficients in the general resistance equation.

The optimization routine used to minimize this error is part of the IMSL Math subroutine package [10]. It is called from the mainline program and uses a direct search complex algorithm to minimize the error between the on-the-road and simulated coastdown curves.

In order to create the simulated distance-time curve, for comparison to the on-the-road data, it must be created using the same initial conditions as the on-the-road test. This means that the simulation must start at the same position on the road and have the same initial velocity as the comparison coastdown.

Because of the data acquisition system 0.1 second finite sampling period, there can be an error in the start position of the car by as much as 0.1 sec. x 27.7 m/s = 2.7 meters, for a coastdown from 100 km/h. This, in addition to the width of the triggering stripe (0.2 meter), can cause an initial position error of the vehicle of about three meters. Because of this potential error, the position of the vehicle relative to the start line is one of the optimized parameters in a simulation. The position of the vehicle must be known in order to assess the grade force acting on the vehicle at any one time.

The starting velocity is also optimized in the analysis routine. Because of the velocity squared relationship of drag force, even a small error in initial velocity can cause significant errors in the values of F_0 and F_2 determined. The initial guess for the start velocity is arrived at by differentiating the beginning of the distance-time curve.

It is in this manner that the F_0 and F_2 coefficients of equation (6) are arrived at from the coastdown data. The error between the on-the-road coastdown curves is therefore minimized using an optimization routine to find F_0, F_2, the starting velocity and the starting position on the test road.

CALM VS. WINDY DATA ANALYSIS

The analysis techniques employed to evaluate vehicle resistance under calm and under windy conditions were very similar. For the calm condition tests, the entire coastdown curve could be analyzed at once. The reason for this is since yaw angle is assumed to be zero, the aerodynamic resistance factor will be a constant value throughout the run. For the windy tests however, yaw angles change continuously throughout the run. Since the drag factor is a function of yaw angle, it too will change during the coastdown. For this reason, windy coastdown data must be analyzed by moving a window of fixed width across the data and analyzing only the data within the window. Figure 8 is a typical example of the data obtained during a windy coastdown run.

The width of the analysis window must be carefully chosen so as not to introduce unnecessary errors. The window must be narrow enough that

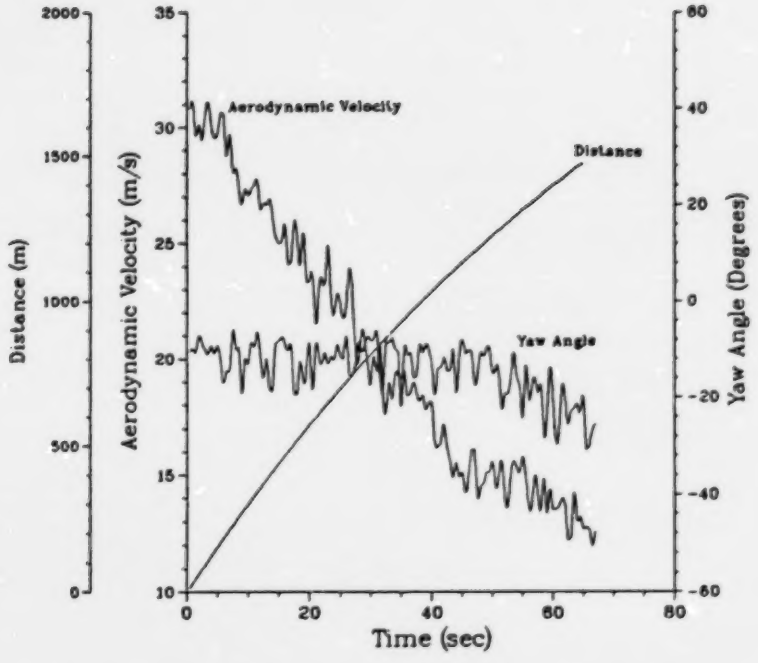

Figure 8 Coastdown Data Obtained Under Windy Conditions

the effect of changing yaw angle and thus F_2 is not masked, and it must be wide enough to average the effects of turbulence [1]. From tests performed on the data with varying window widths, a width of 16 seconds was chosen, moving the window laterally in steps of five seconds, until the end of the run is reached.

The data inside the window was analyzed in much the same manner as the calm weather data. The drag factor F_2 was assumed constant for the time averaged yaw angle (measured) in the window. In this case however, the aerodynamic velocity had been measured and can be used directly in the general resistance equation (7), rather than assuming that aerodynamic velocity is equal to the ground speed of the vehicle plus the wind speed parallel to the track. The new distance is still calculated by equation (9), using the ground speed of the vehicle as calculated in equation (8).

TESTING THE DATA ANALYSIS COMPUTER PROGRAM

Before data analysis began, a method of checking the integrity of the results was desired. The method chosen to accomplish this was to write a computer program, SIMULATE.FOR [9] that, given the resistance coefficients of a vehicle, would perform a simulated coastdown of that vehicle. The simulation program would take road grade and any other necessary terms into account. The output of the program would be distance-time data in the same format as would be received from the micrologger during coastdown tests. This distance-time curve could then be analyzed by the program, COAST or COAST_WIND, and if all worked well,

the resulting resistance coefficients from the analysis program would be those that had initially been put into the simulation program.

In the simulation program, the effects of lift (F_L), centripetal acceleration (F_C), and the velocity dependent term of rolling resistance (F_1) could all be included, or any combination selected in addition to the F_0 and F_2 terms. The simulation program functioned as shown in the following five steps:

1. The initial velocity from which the coastdown was to start was selected. The total resistance force (F_T) acting on the vehicle at this speed was then calculated by the equation,

$$F_T = F_0 + F_1V + F_2V_a^2 + F_G, \tag{10}$$

where $$F_0 = \frac{F_0}{W} \times W_e \tag{11}$$

and $$F_1 = \frac{F_1}{W} \times W_e \tag{12}$$

In equations (11) and (12), W_e, is the effective weight of the vehicle,

$$W_e = W\cos\theta - F_L + F_C. \tag{13}$$

In equation (13), F_L was made equal to the product of a lift factor, F_L', and the square of the aerodynamic velocity of the vehicle ($F_L = F_L'V_a^2$). The centripetal force, F_C, was defined by the equation,

$$F_C = \frac{MV^2}{R} \tag{14}$$

where M = mass of the vehicle

R = radius of curvature of the road at the point of interest

and V = ground speed of the vehicle.

The radius of curvature, R, in equation (14) can be found from the survey data and the expression,

$$R = \frac{\left[1 + \left(\frac{dh}{ds}\right)^2\right]^{3/2}}{d^2h/ds^2},$$

where $\frac{dh}{ds}$ is the slope of the road at the point of interest.

If the program was to simulate a calm weather test, F_2 was a constant. If however, a windy test was desired, F_2 was made equal to a sine squared function of yaw angle:

$$F_2' = F_2 - B\sin^2(Y),$$

where F_2' = yaw dependent drag factor
F_2 = drag factor at 0 yaw
B = sine squared coefficient
Y = yaw angle.

The yaw angle would be calculated vectorily from the user's input of wind speed and direction.

The grade force, F_G, would be calculated from the survey data and the position of the vehicle at that time.

2. The vehicle cumulative distance travelled would be calculated by:

$$D_{new} = D_{old} + V\ ti$$

3. A vehicular acceleration would be calculated for this time step, ti:

$$-a = F_T/M_e.$$

4. A new vehicle ground velocity for this time step was then calculated by:

$$V_{new} = V_{old} + a\ ti.$$

5. A new aerodynamic speed and yaw angle would be calculated based on the new ground speed.

Steps 1 to 5, above, were repeated with a computer time increment of ti = 0.001 seconds, until a minimum ground speed of 30 km/h was reached.

SIMULATE.FOR proved to be a very useful tool for developing and testing the analysis program. The results of some of the simulation tests will be presented below.

The first test conducted consisted of simulating a coastdown pair on the test road selected. The simulation coefficients selected were:

F_0 = 40.0 N
F_1 = 0.0 N/km/h
F_2 = 0.009 N/(km/h)^2
F_L = 0.0 N/(km/h)^2
F_C = neglected
wind = 0.0 km/h.

The magnitudes of these coefficients were chosen for Nexus based on the previous coastdown work of Johnston [5]. The results of the analysis program are shown in Table 1.

In the table, the column labelled Average Error In Fit is the absolute value of the average difference between the coastdown curve input, in this case simulated data, and the coastdown curve generated by the analysis program using the analytical coefficients.

In order to show the significant effect of grade compensation in the computer program, an analysis run was conducted omitting this function. For the run, the same data file from SIMULATE as in Table 1 was analyzed by COAST. COAST however was slightly modified in this case to set the grade force equal to zero, at all positions along the coastdown. The results of this analysis appear in Table 2.

Table 1 Results of 1st Simulation Test

Run	F_0 N	F_2 N/(km/h)^2	Average Error in Fit m
East	40.00	.00898	.005
West	40.01	.00899	.005
Avg.	40.00	.00899	.005
True	40.00	.00900	
% Err.	.025	-.111	

Table 2 Analysis Results Neglecting Grade Force

Run	F_0 N	F_2 N/(km/h)^2	Average Error Between Curves m
East	75.83	0.00400	0.85
West	54.60	0.00422	2.48
Mean	65.22	0.00411	1.68
True	40.00	0.00900	
% Err.	63.1	-54.3	

It is obvious from the results in the table that the grade force cannot be neglected if meaningful or repeatable results are desired.

The third test performed was to see if the assumption, that vehicle centripetal force could be neglected, was valid. The simulation coefficients selected were the same as for test 1, except F_C was taken into account. In the analysis however, the centripetal force was neglected. The results are as follows:

Because of the very small percent error between the assumed coefficients, neglecting the centripetal forces, and the coefficients put into SIMULATE, it was deemed acceptable to neglect vehicle centripetal accelerations during analysis for this road. It would, however, be recommended to check this assumption for any other coastdown road if larger hills or valleys are present.

A test was also conducted to study the effect of including the

Table 3 Results of Centrifugal Influence

Run	F_0 N	F_2 N/(km/h)^2	Average Error in Fit m
East	39.99	.00899	.005
True	40.00	.00900	
% Err.	-.025	-.111	

velocity dependent term of the rolling resistance, F_1, with the F_0 and F_2 terms. Dayman [9] has found C_{Rv} for a standard Uniroyal Radial tire to be 0.000070 per mile per hour at normal inflation pressures. This tire is similar to the Michelins of the Nexus prototype, so for trial purposes its value was used. This C_{Rv} coefficient would translate to an F_1 factor of 0.175 N/km/h for the 4041 N Nexus vehicle, or 17.5 N of resistance at 100 km/h. It is believed that this value is much higher than that of the test vehicle since during coastdown tests, the Nexus tires were inflated to 414 kPa, over twice normal inflation pressure.

In spite of this fact, a test was performed to determine the effect of neglecting this F_1 term, if it were present. The following values were input to the simulation program,

F_0 = 40.0 N
F_1 = 0.175 N/km/h
F_2 = 0.009 N/(km/h)^2
F_L = 0.0 N/(km/h)^2
F_C = neglected
wind = 0.0 km/h.

Analysis of the simulated coastdown curve was conducted without taking F_1 into account. The following results were obtained:

Table 4 Results of Neglecting F_1

Run	F_0 N	F_2 N/(km/h)^2	Average Error m
East	45.59	0.01051	0.025
True	40.00 F_1 = 0.175	0.0090	
% Err.	14.0	16.8	

It can be seen from the above results that the effects of the F_1 coefficient in the data is distributed between the F_0 and F_2 terms in the analysis.

Because of this, an addition was made to the analysis program to optimize an F_1 term in addition to the already optimized, F_0, F_2, starting velocity and starting position values. This new program functioned very well with the simulated data including an F_1 term of 0.175 N/km/h. The results can be seen in Table 5 below.

Table 5 Results of Including F_1 Term in the Analysis

Run	F_0 N	F_1 N/km/h	F_2 N/(km/h)^2	Error m
East	39.91	0.177	0.00897	.004
True	40.00	0.175	0.0090	
% Err.	-.23	1.2	-.33	

These results indicate a much better fit of the data, with the analysis program obtaining F_0, F_1 and F_2 terms very close to those put into SIMULATE.

When an attempt to find the F_1 term of the on-the-road data was made, the F_1 found varied several hundred percent from run to run. This is thought to have been caused because the high inflation pressures of the Nexus tires make the F_1 present, too small to accurately measure. The F_1 found in the analysis would then be an attempt by the computer program to lessen the residual errors in the difference between the curves. For this reason, the analysis program used for the on-the-road data did not attempt to find the F_1 term of rolling resistance.

As mentioned previously, wind tunnel testing showed the Nexus vehicle to have a zero degree yaw lift factor of -0.0105 N/(km/h)^2 that reached zero N/(km/h)^2 at about 16 degrees yaw. The fourth test performed was to study the effect of neglecting this coefficient. The simulation coefficients input were:

F_0 = 40.0 N
F_1 = 0.0 N/km/h
F_2 = 0.009 N/(km/h)^2
F_L = -0.0105 N/(km/h)^2
F_C = neglected
wind = 0.0 km/h.

The results of the analysis, neglecting lift factor can be seen in Table 6.

The reason for the large (one percent) error in the F_2 value obtained is that lift is a V^2 dependent force. The effects of lift will be seen in F_2 which is also V^2 dependent. The average error between the curves is still very small, even neglecting the lift. It was decided that neglecting lift effects in this analysis would be acceptable.

In order to determine the error of velocity effect in the

Table 6 Results of Simulation Test Neglecting Lift Factor

Run	F_0 N	F_2 N/(km/h)^2	Average Error m
East	39.99	0.00909	0.0048
True	40.00	0.0090	
% Err.	-0.03	1.00	

circumference of the tires, a fourth test was performed. Simulation data was created by SIMULATE.FOR, with the circumference of the tire equal to 1.841 meters. All other simulation coefficients were selected the same as for test 1. For the analysis however, the circumference of the tire was assumed to be 1.838 meters.

The results from this test seen in Table 7, showed a percent error in F_0 only slightly higher than the idealized test #1. The error in F_2 is no different than test 1. From this test it was decided that the small velocity dependency of tire circumference could be neglected with little or no error.

Table 7 Results of Tire Growth

Run	F_0 N	F_2 N/(km/h)^2	Average Error m
East	39.86	0.00901	.005
True	40.00	0.0090	
% Err.	-.35	0.111	

In order to test COAST_WIND, the value of yaw angle and F_2 was allowed to change with vehicle velocity. SAE Recommended Practice J1263 uses a sine squared relationship for the dependency of drag on yaw angle. For the purpose of the simulation, the expression

$$F_2 = 0.009 - 0.25 \sin^2(\text{Yaw}),$$

was used in SIMULATE. The coefficients for zero yaw and the sine squared term were chosen based on the previous work of Johnston.

The first part of the testing of COAST_WIND, was to select the best window width, within which to analyze the data. Tests were performed with several window widths, over two different bands of yaw angle, on data created with SIMULATE. The coefficients put into SIMULATE were:

F_0 = 40.0 N
F_1 = 0.0 N/km/h
F_2 = 0.009 - .025 $\sin^2$(Yaw) N/(km/h)^2
F_L = 0.0 N/(km/h)^2
F_C = neglected
wind = 5 and 25 km/h @ 90 degrees to track

The results of this test, varying the window width, can be seen in Figure 9.

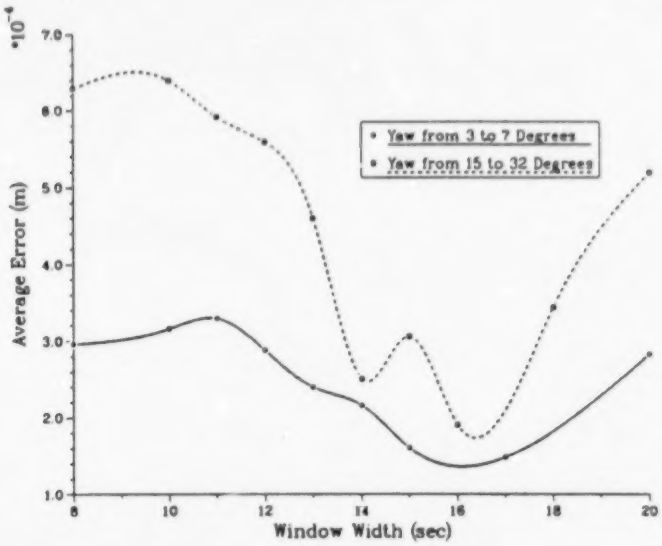

Figure 9 Comparison of RMS error for different window widths and two bands of yaw angles

Figure 9 compares the values of F_2 obtained at a certain yaw angle to what they should be according to the F_2 expression used by SIMULATE. The figure shows that the minimum width for both bands of yaw (3 to 7 degrees and 15 to 32 degrees) is 16 seconds.

Figures 10(a) and (b) show the results of running COAST-WIND on the simulated data, with a window width of 16 seconds. In the figures, the square symbols represent the values of F_2 evaluated for a corresponding yaw angle, the solid curve is the least squares best fit of the data to a sine squared function and the dashed line is the F_2 vs. yaw function used by SIMULATE.

For the low yaw angle data, the difference between estimated and actual F_2 at zero yaw is only 0.9% (Table 8) however, the sine squared coefficient estimated is 32% higher. The high yaw angle data gives a much better overall comparison, with F_2 at zero yaw 2.8% high and the sine squared coefficient 7.6% high. The average error for the F_0 term arrived at, is 1.25%.

The reason for the larger error in the sine squared coefficient of the low yaw angle data, is the fact that the curve is very flat at these

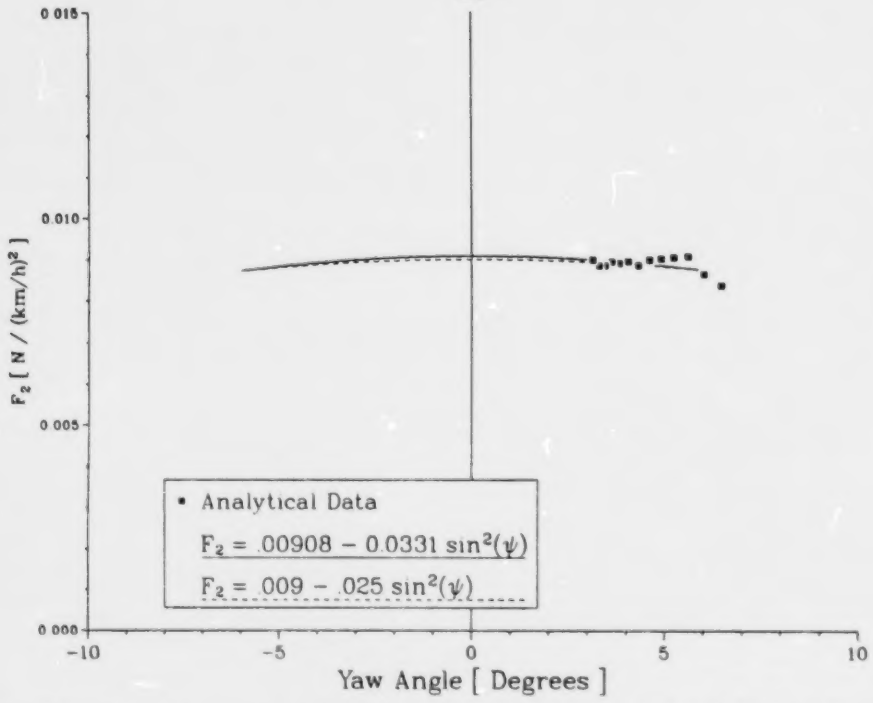

Figure 10(a) F_2 versus yaw relationship for simulated, low yaw angle data

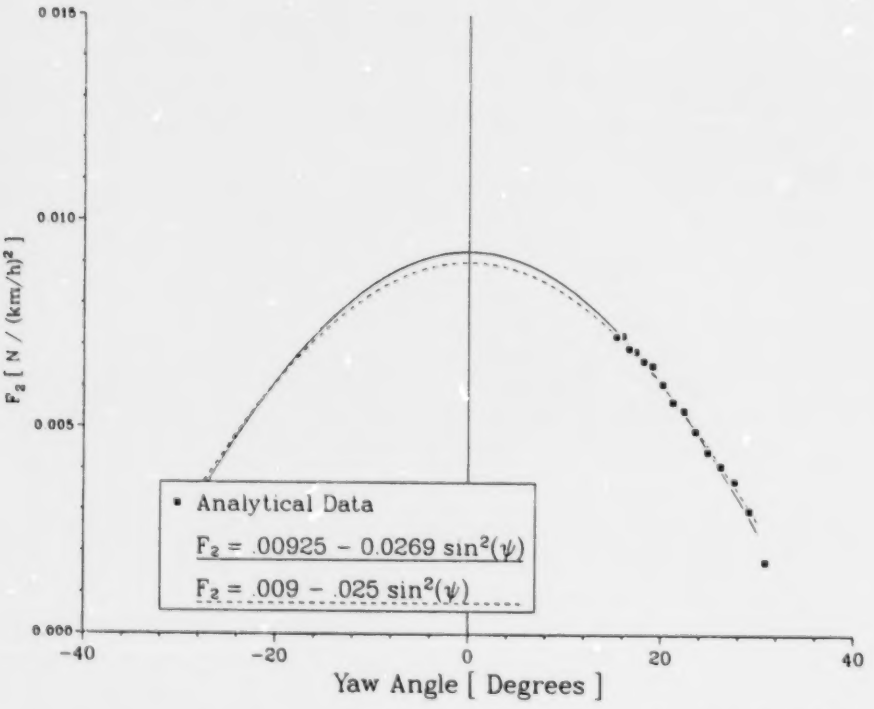

Figure 10(b) F_2 versus yaw relationship for simulated, high yaw angle data

low yaw angles. It is difficult to fit a proper sine squared curve to data that is changing so little.

Table 8 Results of Windy Coastdown Simulation

Run	F_0 N	F_2 N/(km/h)^2	Average Error m
East (low yaw)	40.33	$0.00908-0.0331\sin^2(\text{yaw})$	0.006
East (large yaw)	40.69	$0.00925-0.0269\sin^2(\text{yaw})$	0.012

CALM WEATHER ROAD TEST RESULTS

The results of the calm weather coastdown tests are summarized in Table 9.

Table 9 Results of Calm Weather Coastdown Tests

Configuration	# of runs averaged	F_0/Sdev N	C_r/Sdev	F_2/Sdev N/(Km/h)^2
Standard	84	43.34/2.57	.0108/.0006	.0106/.0006
Headlts. Out	20	43.64/2.50	.0109/.0006	.0128/.0006
Extra Wt.	8	45.53/1.47	.0109/.0004	.0104/.0002

In Table 9, F_0 and F_2 have been corrected to standard temperature and pressure while F_0 has been converted to a coefficient of rolling resistance C_r so that comparison could be made between tests at the standard vehicle weight of 4012 N, and that of the vehicle with an added weight (4179 N).

As the table indicates, resulting values of C_r are very repeatable as is the value for F_2 in the Standard and Extra Weight cases. The value of F_2 is higher for the "Headlights Out" case since the extended headlights increase the frontal area and disturb the flow. It should also be noted that the value of C_r for this configuration does not change significantly from the Standard case.

The SAE Recommended Practice J1263 requires that the standard deviation of the rolling resistance F_0 be less than 11 N, or 5% of the mean, and that of the drag factor, F_2, be less than 0.011 N/(km/h)^2 or 3% of the mean. In each case of the results , the absolute value of the standard deviation is lower than that required by the Recommended

Practice. In most of the cases however, the standard deviation is higher than the maximum allowed percentage of the mean.

The reason for the seemingly large standard deviation in the results is that many outside influences, such as changing wind speed and direction, cannot fully be accounted for. Also introducing noise into the system are oscillations in the road grade and the crown of the road. The driver constantly needs to input steering corrections and as a result never drives down precisely the same coastdown path twice.

The results of the calm condition tests clearly indicate that this analysis method performs admirably in determining the resistance coefficients for a vehicle coasting on a road with a varying grade. The standard deviation in the results is not excessive and can be attributed to atmospheric (changes in wind speed and direction beyond the dynamics of the instrumentation) as well as mechanical (steering inputs) effects.

WINDY WEATHER ROAD TEST RESULTS

Figure 11 presents the results of the analysis of a typical windy weather coastdown data set. It consists of twelve individual coastdowns. On this particular day of testing, there was a 30 km/h wind from the northwest.

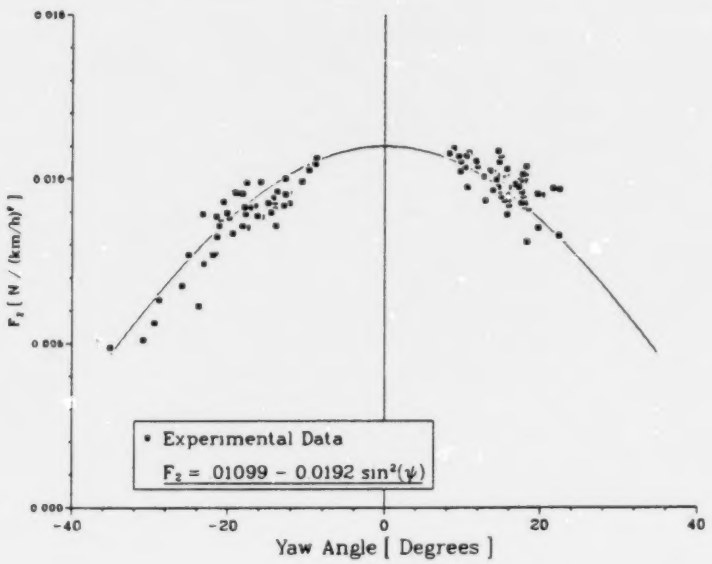

Figure 11 Typical F_2 vs. yaw curve resulting from a windy coastdown analysis

In the figure, the symbols represent the resulting F_2 of the analysis of a particular 'window' of data. The curve in the figure, is the least squares best fit, to a sine squared function, of the data. In this case, the function turned out to be:

$F_2 = 0.01099 - 0.0192 \sin^2 (\text{Yaw})$.

Probably the most noticeable point of this function is the negative sine squared coefficient. The significance of the sign of this term is that it shows the aerodynamic force decreases with yaw angle. This is unlike most road vehicles whose aerodynamic resistance increases with yaw angle.

The zero yaw drag factor of 0.0109 is only 2.8 percent higher than the drag factor measured for the calm condition tests. This is an expected increase because of the wind speed and direction measuring instruments being mounted on the vehicle, disturbing the flow. The average rolling resistance measured for this data set is 40.67 N with a standard deviation of 1.9 Newtons, a value 6.2 percent lower than that measured for the calm condition tests.

In order to get a better averaging effect, all of the windy condition data sets were analyzed and the F_2 data grouped together to fit to a sine squared function. When this was done, the results seemed excessively scattered although they still fit a sine squared function, with F_2 decreasing at yaw.

In an attempt to determine the reason for the larger amount of scatter, the data was broken into two groups: one, all data obtained when the wind was from the south, and the second, data with a north wind.

Comparing the two groups of data, it was apparent that the majority of the scatter in the results was occurring from the runs which took place when the ambient wind was from the south. A possible reason for the scatter in the data with a south wind is that the land south of the test road had more clumps of bushes and trees than the relatively open prairie on the north side. The trees on the south side of the road would introduce a larger amount of turbulence into the wind and thus a greater amount of noise in the aerodynamic speed and yaw angle data recorded during a run. In addition to this there would be scatter due to a transition in the data when the coasting vehicle emerged from behind a clump of trees. For this reason it was decided that the data recorded when there was a south ambient wind, would be set aside because of the large amount of scatter that it introduced into the results.

Figure 12, shows the F_2 vs yaw results for 44 windy coastdown runs. The drag factor (F_2) at zero yaw is only 2.8 percent less than the average F_2 value obtained from the calm condition tests. The average F_0, or rolling resistance for these 44 runs is 40.63 Newtons with a standard deviation of 1.84 N, which compares closely with the 43.34 Newton value obtained for the calm condition tests.

A 3-D histogram of resulting values F_2 in Figure 13 shows the tendency for the drag of the vehicle to decrease with yaw angle. Extrapolating the sine squared function that has been fit to the data ($F_2 = .0103 - .015 \sin^2(\text{yaw})$), we find that the vehicle would have zero drag at a yaw angle of 55 degrees.

WIND MEAN AVERAGED DRAG

The wind mean averaged drag (WMAD)[2] is the characteristic of a vehicle describing its 'average drag', taking yaw angle into account. It is the average aerodynamic drag of the vehicle assuming an annual mean wind speed, and that the wind will approach the vehicle with equal probability from any direction.

The WMAD of the Nexus vehicle will be calculated based on a mean

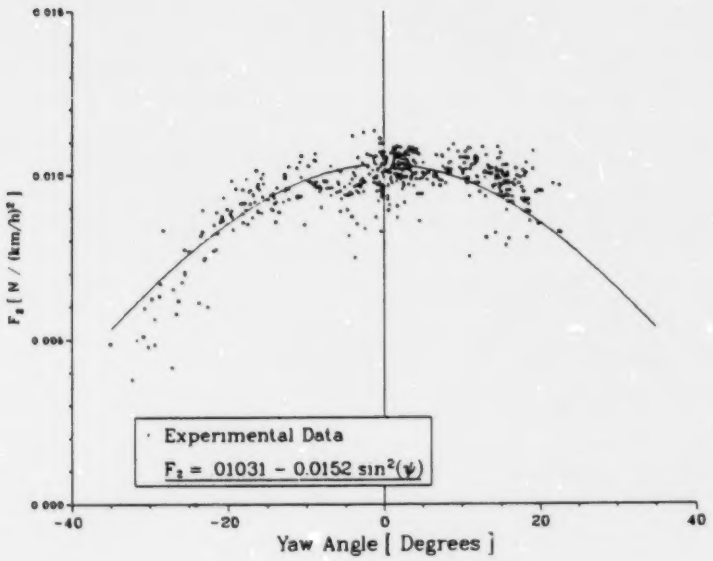

Figure 12 Yaw dependency of drag factor for the runs with a north wind

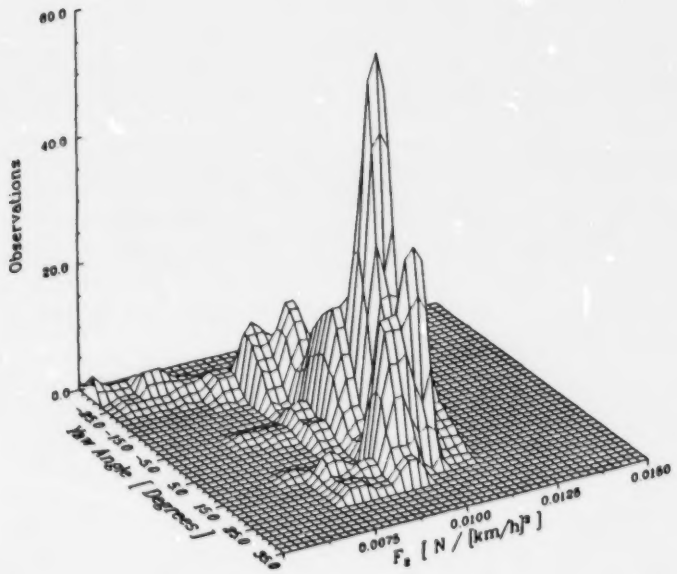

Figure 13 Histogram of F_2 values obtained for 44 windy coastdowns

wind speed of 14.12 km/h. This is the average wind speed for Western Canada. When the WMAD is calculated as outlined in reference 2, a value of 0.01036 N/(km/h)^2 is obtained for F_2, based on a vehicle speed of 100 km/h, and the F_2 (Yaw) relationship,

$$F_2(Yaw) = 0.0104 - 0.015 \sin^2(Yaw).$$

If we recall that most road vehicles experience an increasing drag with yaw angle, a quick comparison can be done for a hypothetical vehicle with the same zero yaw drag but having it increase with yaw angle, as in the expression:

$$F_2(Yaw) = 0.0104 + 0.015 \sin^2(Yaw).$$

For this hypothetical vehicle, the WMAD, F_2 would be three percent higher than for the Nexus vehicle at 0.01067 $N/(Km/h)^2$. This is not a dramatic increase but it does show the benefit of the decreasing drag phenomena.

EXPLANATION OF DECREASING DRAG PHENOMENA

The phenomena of decreasing drag with increasing aerodynamic yaw angle can be explained by looking at a simple airfoil. The shape of the Nexus body, in plan view, is that of a truncated airfoil. Referring to Figure 14, an airfoil with an aerodynamic velocity, V_a and a yaw angle, , will develop a net lift force, L, perpendicular to V_a, and a drag force FD, parallel to V_a. These lift and drag forces can be resolved into forces parallel and perpendicular to the direction of travel of the airfoil, assuming it to be a road vehicle. When the yaw angle becomes large enough, the component of lift parallel to the direction of travel becomes greater than that component of drag and the object begins to develop a thrust, rather than drag, in the direction of travel. One would expect that once the yaw angle became too large, the airfoil would stall and no lift would be developed. Wind tunnel tests have shown however [11], that for an airfoil with a short aspect ratio such as the Nexus vehicle, a stall does not appear to occur. It is believed that this is the reason for the continuing decreasing drag with yaw phenomena, experienced by the Nexus vehicle.

DISCUSSION

This research has measured aerodynamic and rolling resistance values for the Nexus commuter vehicle under calm as well as windy weather conditions. The tests were performed with the vehicle tires inflated to a pressure of 414 kPa, on a test road with hills and valleys and a steepest grade of 0.7%.

The results obtained can be compared to those of Johnston [5]. It should be pointed out however, that the results of Johnston were obtained from coastdown tests on a road with a measured grade of 0.0%. The analysis technique used by Johnston was the Korst and White method as adopted by the SAE [3]. In his analysis metnod, the individual runs whose calculated resistance values are further than acceptable from the mean value, are rejected, until the standard deviation of the test is acceptable. The results obtained in this research, have however included all runs.

Table 10 compares results and standard deviations between the authors and Johnston.

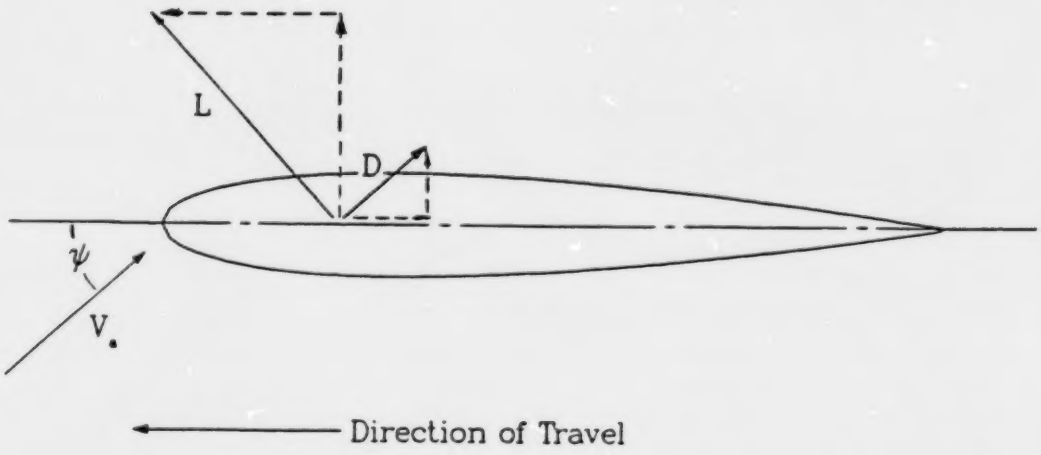

Figure 14 Resolution of simple airfoil forces

Table 10 Comparison of Results to The Work of Johnston

	Remenda	Johnston
C_T(Sdev %)	0.0108 (5.6%)	0.0098 (6.3%)
F_2(Sdev %)	0.0106 (5.7%)	0.0103 (5.2%)
C_T(Sdev %) Headlts. out	0.0109 (5.5%)	0.0101 (7.1%)
F_2(Sdev %) Headlts. out	0.0128 (4.7%)	0.0121 (5.5%)

As can be seen in the table, the results are very nearly the same in magnitude and standard deviation for both Remenda and Johnston. The slightly higher values for F_2 of Remenda, can be attributed to a slight increase in the frontal area of the vehicle since the tests of Johnston due to the addition of exhaust pipes extending from the vehicle underside. One should recall again that while both sets of tests were done in calm conditions, those of Remenda were conducted upon a road with significant grade while those of Johnston were done on a level road. It is obvious from these results that using this new method of

coastdown testing and analysis, results as good or better than those previously conducted on level roads, can be obtained on roads with significantly variable grades.

While Dayman [8] has been able to measure the velocity dependent rolling resistance coefficient for a tire, recent research by Ivens [12] concludes that for 13 inch European tires, the rolling resistance is independent of velocity below 160 km/h. It is believed that because of this and the fact that the Nexus tires are operating far below their rated load [13] coupled with the fact that the tires were at over twice normal inflation pressure, the velocity dependent rolling resistance coefficient for these tests was too small to measure.

The value measured for velocity independent rolling resistance coefficient (C_r = 0.0108) is nearly identical to that measured by Dayman for a Uniroyal Radial (C_r = 0.0109). This is an indication that the method used and results obtained to calculate this value for the Michelin tires of Nexus are reasonable.

The standard deviations for the values of aerodynamic drag and rolling resistance can be attributed to variables not accounted for in the data analysis procedures. These variables are:

1. Change in atmospheric conditions (eg. wind gusts and turbulence, changes in wind direction, changes in humidity from day to day).

2. Variations in road grade. Although the road grade was measured every five meters, there will be changes in grade between the measured points that are not accounted for.

3. The driver will constantly need to correct the direction of travel because of mechanical slack in the steering system and the crown of the road. These steering inputs will cause extra rolling resistance and because the vehicle never travels down exactly the same path twice, the rolling resistance will change.

4. Depending upon the speed and direction of the wind, the driver will need to input a small steering correction to counteract the crown of the road. Looking at Figure 15(a) it can be seen for the vehicle moving out of the page, the driver will need to input a steering effect to negate the tendency of the vehicle to roll off the road. In addition to this, the wind tending to push the automobile off the road will necessitate a steering input in the opposite direction. In Figure 15(b) however, the wind being from the opposite direction will tend to decrease the amount of steering input needed to counteract the road crown. This changing amount of necessary steering input will cause a variation in rolling resistance from run to run and day to day. A road without a crown, however, will alleviate the need for steering corrections to overcome the tendency to roll down the crown. It will not however, remove the need to counteract the side force due to the wind.

It is believed that the variables discussed here could account for the observed standard deviations in the values calculated. Results of the coastdown test performed in crosswinds demonstrate a surprising phenomenon. This phenomenon is described as decreasing drag at yaw.

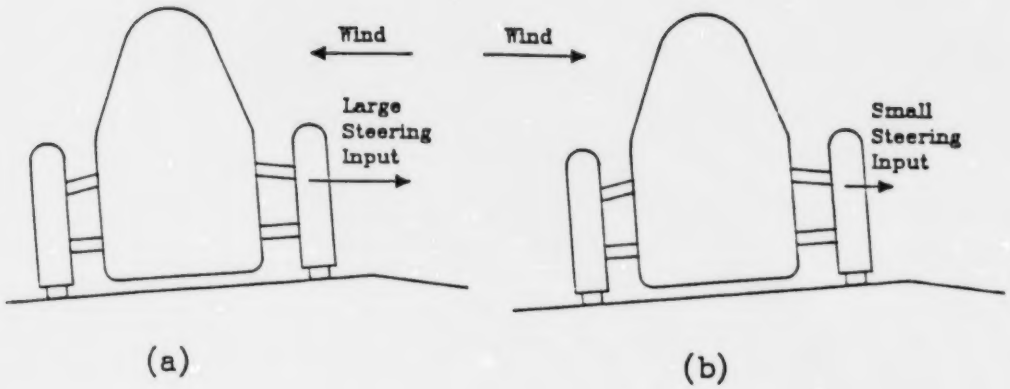

Figure 15 Combined effects of road crown and wind

The drag force on the vehicle is observed to decrease as the wind relative to the prototype deviates from head-on. The reason for this decreasing drag phenomenon can be explained considering a simple airfoil and resolving the forces onto an appropriate axis system.

The reason for the scatter in the windy condition tests can be attributed to atmospheric turbulence in the wind speed and direction. The stronger the ambient wind, the more turbulence there seems to be present. Although much of the turbulence can be filtered out by smoothing the data and averaging a wider window of data, it is still present to cause scatter. In spite of this scatter, the decreasing drag with yaw tendency is unequivocal. In addition to this, the zero yaw drag factor (F_2) obtained by fitting the data to a sine squared function is only slightly larger than that obtained for the calm condition tests. This slight increase in drag can be attributed to the addition of the Kiel probe and boom to the car, somewhat disturbing the flow.

CONCLUSIONS

Based upon the results of on-road coastdown tests conducted on the Nexus commuter prototype, the following conclusions can be drawn:

1. Compared to resistance values obtained for the same vehicle coasting on a level road, comparable results have been obtained for the vehicle coasting under grade variable conditions.

2. The simulation/optimization approach to coastdown data analysis works very well, enabling both aerodynamic and rolling resistance values to be calculated under windy and grade variable conditions.

3. The computer program SIMULATE was an invaluable tool in testing and debugging the analysis programs COAT and COAST_WIND. It allowed he effect of neglecting certain variables to be studied, knowing what the results should be.

4. The value of the zero yaw drag factor for the Nexus vehicle was calculated to be 0.0106 $N/(km/h)^2$ with a standard deviation of 0.0006 $N/(km/h)^2$, for the headlights retracted case. For the headlights extended case, this factor was calculated to be 0.0128 $N/(km/h)^2$, the standard deviation again being 0.0006 $N/(km/h)^2$.

5. The velocity independent value of rolling resistance coefficient of Nexus was found to be 0.0109 with a standard deviation of 0.0006.

6. The Nexus vehicle exhibits a unique decreasing drag with yaw phenomena when studied under windy conditions. The analytical drag factor (F_2) vs. Yaw data when fit to a sine squared function takes the form:

   $$F_2 = (0.0104 - 0.0152 \sin^2(\text{Yaw})) \ [N/(km/h)^2].$$

   The calculated value of rolling resistance coefficient has a value of 0.0101 with a standard deviation of 0.0005 when coasting under these conditions.

7. The velocity dependent value of rolling resistance for the Nexus vehicle, under the test conditions, appears too low to measure accurately, so it is included as part of the F_0 and F_2 terms.

8. Neglecting the centripetal force acting on the coasting vehicle as it negotiates hills and valleys of this test track will have little or no effect on the measured resistance values. The validity of neglecting this force should be checked for other vehicles or test roads.

9. The small lift force acting on the Nexus vehicle can be neglected without appreciably affecting the calculated results.

10. The small velocity dependence of tire circumference had little effect on the resistances calculated. At higher speeds than tested or lower tire pressures, this may not be the case.

It is believed that this research will enable future coastdown tests to be conducted more readily on almost any smooth test road under most wind conditions by using the simulation/optimization analysis technique described herein.

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